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Power Quality of Distributed Wind Projects in the Turbine Verification Program

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POWER QUALITY OF DISTRIBUTED WIND PROJECTS IN THE TURBINE VERIFICATION PROGRAM

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Abstract

The Electric Power Research Institute/U.S. Department of Energy (EPRI/DOE) Turbine Verification Program (TVP) includes four distributed wind generation projects connected to utility distribution feeders located in Algona, Iowa; Springview, Nebraska; Glenmore, Wisconsin; and Kotzebue, Alaska. The TVP has undertaken power quality measurements at each project to assess the impact that power quality has on the local utility grids. The measurements and analysis were guided by the draft IEC 61400-21 standard for power quality testing of wind turbines. The power quality characteristics measured include maximum power, distribution feeder voltage regulation, reactive power, and harmonics. This paper describes the approach to the measurements, the unique electrical system features of the four projects, and an assessment of measured power quality relative to limits prescribed by standards. It also gives anecdotal stories from each project regarding the impact of power quality on the respective distribution feeders.

Introduction

EPRI and DOE initiated the TVP in 1992 to evaluate prototype advanced wind turbines and to provide a bridge from development programs to early production models of commercial wind turbines. Central and South West Services in Texas and Green Mountain Power Corporation in Vermont were chosen through a competitive solicitation to host the first two TVP projects. TVP's involvement in these projects ended in 1999 and 2000, respectively.

Two public utility partnerships were also selected to participate in the TVP in 1997 through a Request for Proposals, which focused on evaluating distributed wind generation using turbines connected directly to the electric distribution system. The Iowa Distributed Wind Generation Project in Algona, Iowa, and the Nebraska Distributed Wind Generation Project in Springview, Nebraska, were built in the fall of 1998.

In addition to the projects chosen through TVP solicitations, four utility wind facilities to date have joined the TVP as "associate" projects. These projects receive limited funding from the program but benefit from information exchange and technical assistance. The Associate TVP projects include the Kotzebue Wind Energy Project in Kotzebue, Alaska; the Wisconsin Low-Wind-Speed Turbine Project in Glenmore, Wisconsin; the York Research Corporation Big Spring Wind Farm in Big Spring, Texas; and the Tennessee Valley Authority Buffalo Mountain wind project in eastern Tennessee. The wind turbines in both the Kotzebue and Glenmore projects are interconnected to distribution feeders.

A primary objective for four of the distributed TVP projects is to examine issues related to distributed generation. Relative to the large wind farm concept, distributed wind generation using "clusters" of wind turbines is seen by some to offer lower risk and a more flexible way for utilities to participate in wind energy projects. Such projects are typically connected directly to a distribution line without a dedicated substation, which reduces costs. They may be operated independently or from a central, remote site. As an alternative to the traditional U.S. utility approach of expanding centralized generation, the distributed development model offers opportunities for utilities to address system expansion issues and allows smaller, modular capacity assets to be located nearer to load centers. For a thorough discussion of distributed wind power, refer to *Distributed Wind Power Assessment* by the National Wind Coordinating Committee (NWTC 2001).

Power Quality Characteristics

Power quality is of particular interest for distributed wind applications for two primary reasons. First, the wind turbines are connected to distribution feeders rather than to transmission lines. Distribution feeders are not as electrically "stiff," and are less able to deal with a fluctuating source like a wind turbine. (Stiffness refers to the ability of a feeder to maintain constant voltage during periods of high current.) Secondly, utility customers are typically located on the same distribution line, sometimes relatively close to the wind turbine(s). Without intervening substations or transmission lines, these customers will be more directly exposed to power quality problems should any exist. The variations in output power inherent with wind turbines caused by changes in wind speed, turbulence, wind turbine switching events (e.g. starting, stopping, and switching speeds), and other phenomena have the potential to degrade the power quality of a distribution feeder.

A new international standard for wind turbine power quality is under development by the International Electrotechnical Commission (IEC), IEC 61400-21, "*Wind Turbine Generator Systems–Part 21: Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines"* (IEC 2000). When published, this document will provide a uniform methodology for measuring power quality characteristics of grid-connected wind turbines, including peak power output, reactive power, voltage fluctuations (flicker), and harmonics. These wind turbine electrical characteristics, through interaction with the electrical grid, exert the most influence on the power quality of a particular wind turbine installation.

This study follows the approach of IEC 61400-21 to the extent possible with the data set available to us. The one characteristic we cannot address is voltage fluctuations or flicker. Measurement of flicker using the IEC method requires very high sampling rates, up to 3,000 Hz, which are beyond the capabilities of the data systems being used to monitor these four projects. In addition to the power quality characteristics incorporated in IEC 61400-21, we will also address the voltage regulation of the individual distribution feeders. We will present measurements made on individual wind turbines in the four distributed wind generation projects and compare the data, where applicable, to recognized power quality limits. It is important to note that the pending IEC standard does not provide any criteria for evaluating power quality. We will use American National Standards Institute (ANSI) C84.1-1995 for limits on distribution feeder voltage (ANSI 1995). Recommended limits on harmonics are taken from the Institute of Electrical and Electronics Engineers (IEEE) Std 519-1992 (IEEE 1992).

Data Acquisition

Phaser® power transducers manufactured by Second Wind and installed at the output terminals of individual wind turbines provided the data for this study. These transducers were installed on the low-voltage side of the wind turbine transformers. The data was collected and recorded through Advanced Distributed Monitoring Systems also from Second Wind. This SCADA (supervisory control and data acquisition) hardware was standard on each wind turbine at each TVP site which eliminated any need to install extra equipment in order to obtain the data for this study. The Phasers each reported 1-second average data, and 10-minute averages, maximums, and minimums were recorded by the SCADA.

The power quality of a single turbine at each project site has been evaluated. The lengths of the data sets were selected to be in compliance with IEC 61400-21, which prescribes a minimum of five 10-minute time series of data for each 1-meter per second (m/s)-wide wind speed "bin" from cut-in wind speed (3 to 4 m/s, depending on turbine type) to 15 m/s wind speed. For this analysis, we selected data only from periods when all project turbines were online and producing power. For the Algona and Springview projects, a two-week period was sufficient to meet the minimum data requirements. A two-month period was needed to accumulate sufficient data while all ten turbines were operating at the Kotzebue project. No meteorological tower was available for the Glenmore project, necessitating the use of the turbine nacelle anemometer for wind-speed measurements. Data from the nacelle anemometer did not indicate wind speeds up to the required upper speed of 15 m/s. However, the nacelle anemometer typically reads low while the turbine is operating, and it is expected that sufficient data is available at high wind speeds based on the availability of a large amount of data when the turbine was producing rated or higher-than-rated power. Therefore, we used two weeks of data for this project.

Distributed Wind Generation Projects

Each of the four TVP distributed wind projects represents a unique wind turbine and distribution system combination, as summarized in Table 1. The distribution feeder lengths, location of the projects on the feeders, and stiffness of the electrical systems (represented by short-circuit MVA) are different for each project. The maximum wind power penetration—the portion of the feeder or substation load served by wind power—varies widely. There is also variation in the wind turbine technologies used.

Both the Algona and Springview projects use Zond Z50, 750-kW turbines, with variable-speed, power electronic control of doubly-fed induction generators. These turbines use pitch-controlled blades. The power electronic control in each turbine corrects the power factor to a user-adjustable value. Although the same turbines are used in both projects, the distribution feeder characteristics are quite different. The Algona project is located near the end of a 6-mile-long, weak distribution feeder. The rated output of the three wind turbines, 2,250 kW, is much larger than the minimum feeder load, 250 kW. In addition, these wind turbines may at times exceed 100% penetration on the substation. The Springview project is located very close to its substation at the beginning of a very long distribution feeder (200 total feeder miles). Like Algona, the minimum substation load is less than the rated project output, so reverse power flow through the substation will occur when there are high winds and low load (EPRI 1999a).

The Glenmore project uses two 600-kW Tacke turbines with direct-line-connected, two-speed induction generators and stall-controlled blades. Power factor is corrected by sets of four switched capacitors in each wind turbine. The project is located in the middle of a 12-mile, relatively stiff distribution feeder (EPRI 1998). This project has the lowest penetration on the distribution feeder. The rated output of the two turbines is only 70% of the minimum load on the feeder.

TABLE 1. SUMMARY OF DISTRIBUTED WIND GENERATION PROJECTS

Project	**Algona, Iowa**	**Springview, Nebraska**	**Glenmore, Wisconsin**	**Kotzebue, Alaska**
Rated power - project	2,250 kW	1,500 kW	1,200 kW	660 kW
Number of turbines	3	2	2	10
Rated power - per turbine	750 kW	750 kW	600 kW	66 kW
Turbine model	Zond Z50	Zond Z50	Tacke TW-600e	AOC 15/50
Generator	Wound rotor induction	Wound rotor induction	Squirrel cage induction (4/6 pole switchable)	Squirrel cage induction
Frequency converter	PWM inverter	PWM inverter	None	None
Control method	Variable speed; pitch control	Variable speed; pitch control	Two speeds; stall control	Fixed speed; stall control
Power factor correction	Power electronic Winter: PF=.93 Summer: PF=.90	Power electronic PF = 1.0	Switched capacitors	Fixed capacitors
Reactive power (rated)	User set	User set	122 kVAR	15 kVAR
Distribution voltage	13.8 kV	12.5 kV	24.9 kV	12.5 kV
Distance to substation	6 miles	1 mile	6 miles	5 miles
Feeder miles beyond turbines	0	200 miles	6 miles	0
Feeder load				
Minimum	250 kW	Not available	1,700 kW	100 kW
Average	400 kW	Not available	5,600 kW	Not available
Maximum	1,000 kW	Not available	8,700 kW	300 kW
Substation load				
Minimum	2,000 kW	0	2,700 kW	1,800 kW
Average	5,500 kW	900 kW	8,400 kW	2,500 kW
Maximum	8,200 kW	3,500 kW	13,500 kW	3,900 kW
Short circuit MVA	16.2 MVA	25 MVA	35 MVA	12 MVA

The Kotzebue project uses ten 66-kW Atlantic Orient 15/50 wind turbines. These are constant-speed wind turbines with direct-line-coupled induction generators and stall-controlled blades. Power factor is corrected by fixed capacitors installed on each wind turbine. The project is located near the end of a five-mile distribution feeder. The Kotzebue electric system is an isolated grid, powered by a diesel generating plant with six generators. The minimum load on this grid is about 1,800 kW. The wind power penetration into this grid has been as high as 35% for a 10-minute period. Only one or two of the diesel generators typically supply power at any time; the rest are necessary for redundancy. The grid voltage of the Kotzebue system is not as stable as for the other three TVP projects (EPRI 1999b).

Power Quality Measurements

Peak Power—Comparisons of rated nominal power, rated peak power, and measured peak power for the four sites are shown in Figure 1. The turbine rated power information, both nominal and peak, are taken from the manufacturer's literature. The measured power data are the maximum 1-second and 10-minute averages for the selected turbine in each project. In keeping with IEC 61400-21, these values were all normalized by dividing the value by the rated power of each wind turbine. Note the comparisons of rated peak power to the 10-minute measured peak power. This is a measurement of the highest sustained output from the wind turbine, which could affect power system components such as transformers and conductors whose design limits are based on thermal considerations. For the turbines at Algona and Springview, the measured peak power is essentially the same as the rated peak power. At Glenmore and Kotzebue, the rated peak power is exceeded, but by less than 5%. These excursions above rated power have not caused problems at any of the sites. However, the interconnection design process should consider both the 10-minute and 1-second power output values.

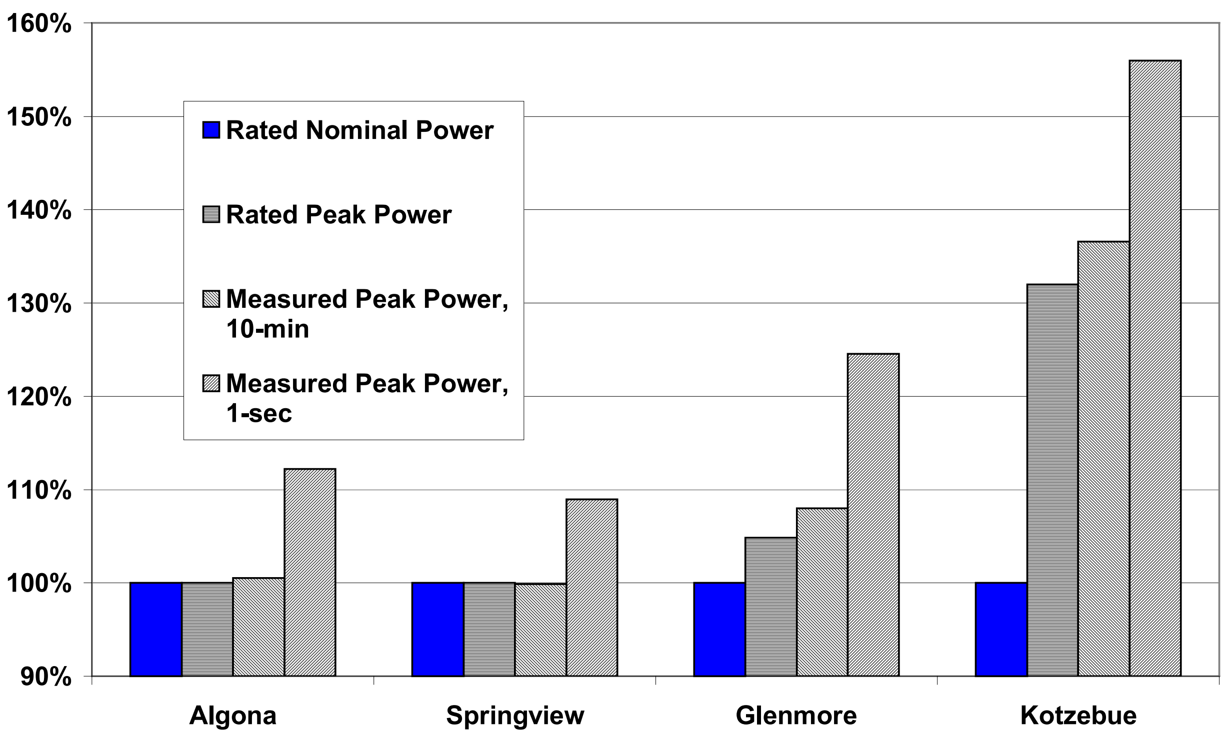

FIGURE 1. COMPARISON OF PERMITTED AND MEASURED PEAK POWER

Feeder Voltage Regulation—The range of 10-minute average voltages observed at the terminals of each wind turbine is plotted in Figure 2. These ranges indicate the ability of the particular distribution feeder to maintain the desired system voltage during wind power generation. For comparison, the voltage range specified in ANSI C84.1 (service voltages, Range A) is also shown. In all four cases, the feeders are able to maintain voltages well within the ANSI limits. Kotzebue shows the largest voltage range of any of the projects. This might be expected given that the Kotzebue utility is a relatively small, isolated grid. The substation serving the wind turbine is, in effect, the entire grid. Even in this situation, voltage regulation is acceptable.

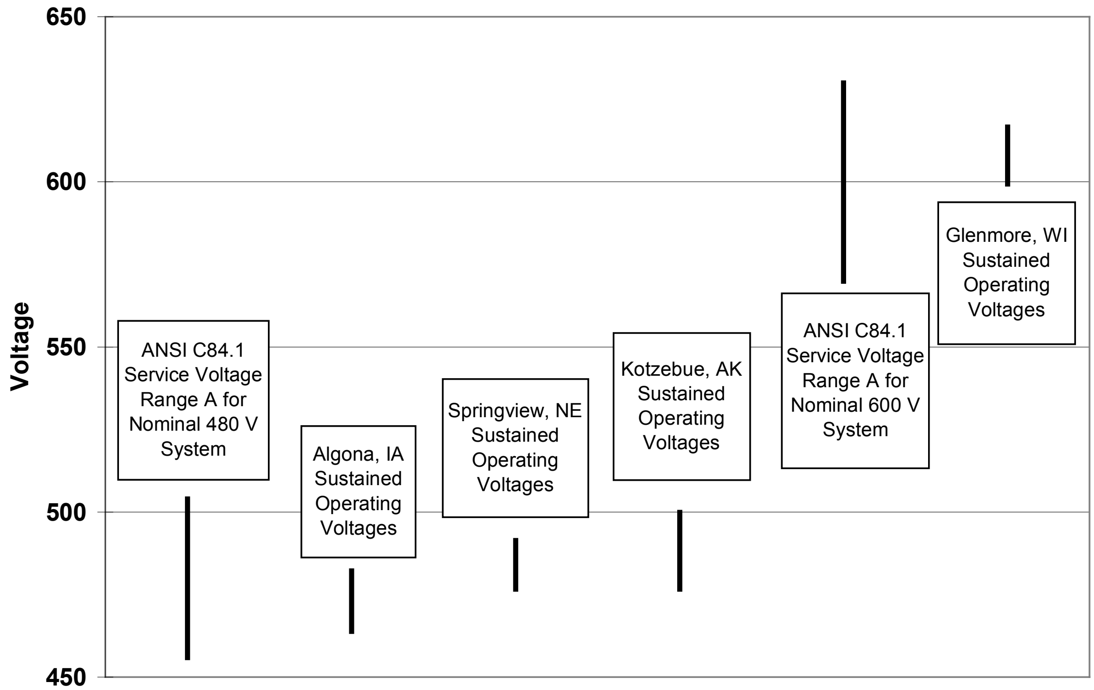

FIGURE 2. FEEDER VOLTAGE REGULATION

Reactive Power—Reactive power is presented as power factor plotted against percent of rated power in Figure 3. At Algona, the power factor is nearly constant at 93% for power levels above 20% of rated. This is a result of the Zond Z50 turbines at this site actively controlling their power factor. The power factor setpoints are changed seasonally, as noted in Table 1, to minimize voltage changes in the feeder. (The Algona data plotted in Figure 3 are from a winter season.) The power factor for the Springview wind turbine, another Zond Z50, also has a nearly constant value above 20% of rated power. It hovers just below the setpoint of 100%.

The wind turbine at Glenmore uses an induction generator, and the power factor is controlled by switching banks of low-voltage capacitors on and off. This is a less accurate control method and results in more variation in the reactive power requirements and the resulting power factor. Nevertheless, the control scheme maintains a relatively constant power factor from 20% output up to full load. The wind turbine at Kotzebue also uses an induction generator, but has only one fixed bank of capacitors. Again, the power factor control is quite good.

There are no standards for reactive power or power factor, however good practice dictates that individual devices on a power system should operate with power factor above 0.9. Three of the four wind turbines operate with power factors above 0.96 over most of their operating range. The fourth, at Algona, was intentionally operated at a lower power factor as noted above.

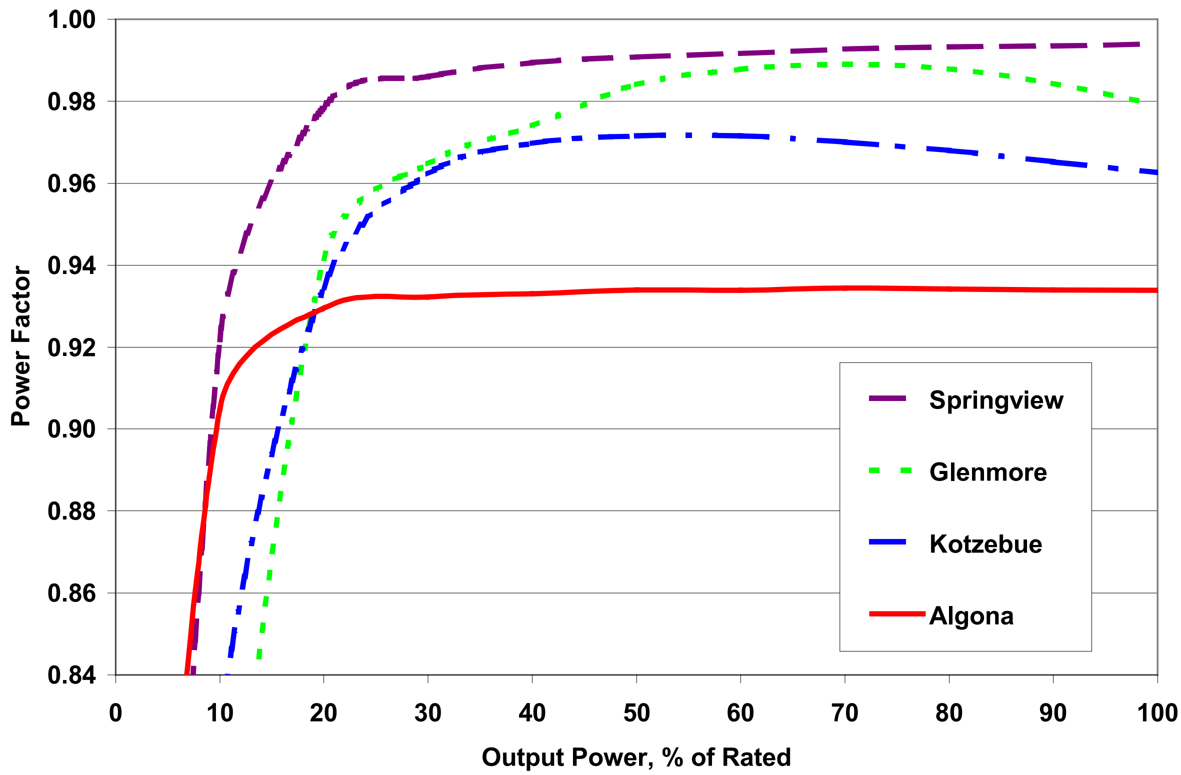

FIGURE 3. POWER FACTOR VS. POWER LEVEL

Harmonics—Total demand distortion (TDD) of the current measured at the four sites has been plotted against percent of rated power in Figure 4, along with the 5% TDD limit recommended in IEEE 519. TDD is the ratio of the root-mean-square value of the total harmonic current to the rated current. The TDD for the Zond Z50 wind turbines at Algona and Springview are remarkably low for variable-speed wind turbines using electronic power converters. Power electronics can be significant sources of harmonics depending upon their design. The TDD averages less than 1.5% for Algona and less than 1.0% for Springview. The differences in the ranges and shape of the data are likely due to the differences in power converter switching frequencies (Springview has a higher frequency) and in the power factor set points.

The TDD for the Glenmore wind turbine increases with power level and reaches 5% near peak power. It is surprising that the TDD for this wind turbine, which uses an induction generator, is actually higher than for the wind turbines with power electronics. The Glenmore turbine does use power electronics for soft-starting of its generator. But, this operation lasts for only a few seconds and should not contribute to the 10-munute-average distortion values reported here. The TDD for the Kotzebue wind turbine averages about 3% over most of its range of operation. In all cases, the TDD has not caused any problems on the distribution systems to which they were connected.

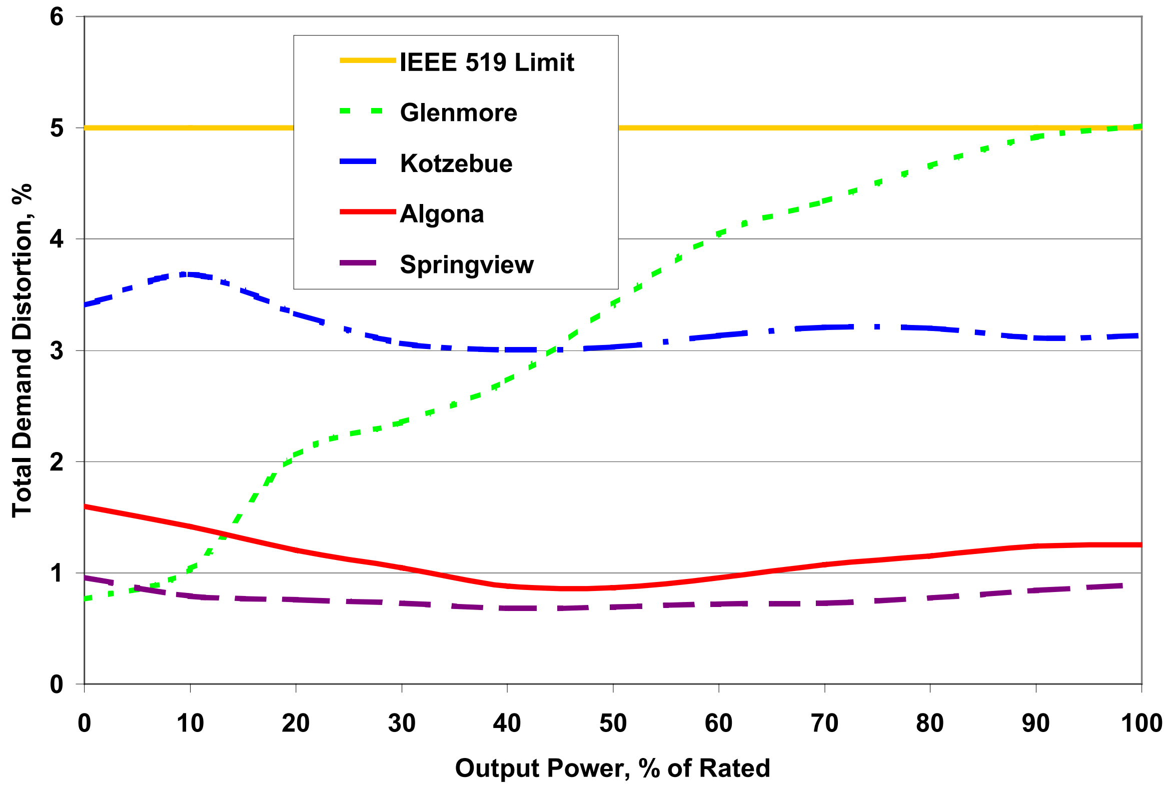

FIGURE 4. TOTAL DEMAND DISTORTION OF CURRENT VS. POWER LEVEL

Utility Power Quality Experience

While measurements are the best basis for evaluating power quality, anecdotal stories from the host utilities are also useful in understanding the impacts of the projects. When the four TVP distributed wind projects were installed, there was little documented experience in the U.S. with utility-scale wind turbines connected directly to distribution lines. Therefore, the host utilities each had some concerns that the turbines might have a negative impact. However, none of the host utilities have reported any customer complaints nor have they observed any power quality problems resulting from the wind turbines.

The wind turbines in Springview created noise on the local telephone lines when they were first installed. This was perplexing because there were no telephone connections to the site and the phone line was physically located across a highway from the distribution line. The phone noise issue was solved through a combination of increasing the switching frequency of the turbines' power electronics converters from 1,000 Hz to 2,000 Hz, modifying the turbines' ground system, connecting a ground tap on the turbines' transformers, and adding additional capacitor filters on the distribution line (EPRI 1999a and EPRI Oct. 2000). The engineer planning the Algona project was concerned about possible voltage variations on the distribution line after the turbines were installed. In response to his concerns, and at his request, Enron designed a new power factor controller for their turbines. Measurements taken after the turbines were installed indicated that the turbines were well behaved and did not cause unacceptable flicker levels or voltage level changes (EPRI 1999a). One particularly sensitive load in Algona is the local hospital, which is connected to the same feeder as the wind turbines. The host utility, Algona Municipal Utilities (AMU), had some concerns about possible power quality impacts the turbines might have on the hospital, but there have been no problems or complaints after more than two years of turbine operation (EPRI Oct.

2000). AMU reports that the distributed generation aspect of the project resulted in cost savings because a substation was not required. The only line improvements made were changing several miles of single-phase line to three-phase.

In Kotzebue the airport is a nearby sensitive load. However, there have been no complaints about power quality impacts at the airport resulting from the turbines. Kotzebue Electric Association (KEA) performed a power quality study after the first three turbines were installed and found that there were no negative impacts (EPRI Dec. 2000).

Like the other projects, the Glenmore turbines have experienced no problems or complaints due to power quality (EPRI Nov. 2000). The engineers from Wisconsin Public Service (WPS) were concerned about the possibility that the turbines might continue to generate power during an outage on the distribution line, thereby posing a safety hazard to linemen. However, they were satisfied that the turbines' safety systems were adequate after spending time with the Tacke engineers during project construction. The positive experience with safety and power quality at the Glenmore project led WPS to install the 9.24-MW Lincoln distributed wind project on their system in 1999.

Substation Power Quality

Another noteworthy study of a TVP distributed wind project's power quality is the paper presented by Mike Hasenkamp at the Windpower 2000 Conference: *"Distribution Line Power Quality Experiences with the Nebraska Distributed Wind Generation Project"* (Hasenkamp 2000). This paper reports on data taken at the substation near Springview to which the two Springview wind turbines are connected. In effect, this data integrates the power quality impact of the two wind turbines and is a snapshot of power quality for the entire feeder. The treatment of voltage disturbances and flicker, in particular, are complimentary to the data presented in this paper. As in our study, Hasenkamp concludes that power quality has not been a problem.

Conclusions

The four TVP distributed wind generation projects have each been operating for more than two years connected to utility distribution feeders. These projects share feeders with residential and commercial electric customers and with sensitive loads including a hospital and an airport. The four host utilities consistently report that they have experienced no power quality problems caused by the wind power on their grids. Perhaps more importantly, they all report that no complaints have been received from customers. These good reports are from projects using diverse technologies—variable speed, two-speed, and constant speed wind turbines. The wind turbine sizes ranged from 66 kW to 750 kW. Three approaches to power factor control were used: active control with power electronics, switched capacitors, and fixed capacitors. And, the wind power penetration on the host substations at times exceeded 100%.

The measurements reported in this paper provide, for the first time, a quantitative assessment of power quality that supports the positive experience of these utilities. The measurements of wind turbine sustained peak power confirmed the manufacturer's peak power ratings to within 5%. Wind turbine reactive power was acceptable, with three of the four projects operating at power factors above 0.96 over most of their operating range. The fourth project was intentionally operated at a lower power factor. Harmonics emitted by the wind turbines were in compliance with the 5% limit given in IEEE 519. Voltage regulation of the distribution feeders complied with the ranges stipulated in ANSI C84.1. The one important electrical characteristic not covered in this study is voltage fluctuations, or flicker. Flicker measurements are recommended to round out this power quality assessment. However, based on the experience to date of the utilities and their customers, we do not anticipate that such measurements will reveal objectionable flicker levels.

Acknowledgements

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